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Chapter 4. PRODUCTIVITY OF FOREST ECOSYSTEMS[1]

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The second criterion under the Montreal Process is the maintenance of the productive capacity of forest ecosystems. This is related to the sustained yield concepts described in Chapter 1, but differs in that it was intended to be extended to the productivity of forest ecosystems as a whole, not just timber. However, over time, revisions to the original wording have resulted in the indicators focussing quite strongly on timber:

2.a Area and percent of forest land and net area of forest land available for wood production.

2.b Total growing stock and annual increment of both merchantable and non-merchantable tree species in forests available for wood production

2.c Area, percent, and growing stock of plantations of native and exotic species

2.d Annual harvest of wood products by volume and as a percentage of net growth or sustained yield

2.e Annual harvest of non-wood forest products

In this chapter, we examine both the factors affecting forest ecosystem productivity, and the ways that forest management can influence these. Much forestry training is related to the manner in which productivity can be measured and monitored, but here we assume that readers have this basic level of training, and it is not further elaborated. For those unfamiliar with forest inventory techniques, there are a variety of textbooks available, but many of the field techniques are best learnt through hands-on training in the forest.

Environmental controls on plant productivity

The ultimate source of energy for life on earth is light from the sun. Pigments in the green tissues of plants absorb light and capture its energy, which is then stored through the manufacture of carbohydrates from simple inorganic compounds – carbon dioxide and water. This energy-trapping process is called photosynthesis. A simplified equation is as follows:

[1] Minor edits were introduced to this text during the final publication of the book. Readers are encouraged to consult and cite the published book and chapters. Book can be adquired at: https://www.routledge.com/Sustainable-Forest-Management-From-Concept-to-Practice/Innes-Tikina/p/book/9781844077243

Photosynthesis: $6\ CO_2 + 6\ H_2O$ + sunlight energy → $C_6H_{12}O_6 + 6\ O_2$ (Eq. 4.1)

Productivity of an ecosystem is the amount of biomass produced by plant photosynthesis per unit of surface over a given period of time. It can be expressed as energy units, or more commonly, as dry organic mass units (kg ha^{-1} $year^{-1}$). The total energy fixed through photosynthesis in a given year is called Gross Primary Production (GPP). Some of this production is used by plants to obtain energy for metabolic activities through the process of respiration:

Respiration: $C_6H_{12}O_6 + 6\ O_2$ → metabolic energy + $6\ CO_2 + 6\ H_2O$ (Eq. 4.2)

The difference between GPP and respiration yields Net Primary Production (NPP). This is the actual amount of biomass available for plant growth (Begon *et al*. 2006).

The rate at which biomass is created by photosynthesis depends on two main plant features: leaf area, and the efficiency in which leaves capture and use light. Both features can be limited by available sunlight, carbon dioxide (CO_2), water, and mineral nutrients. These are the resources needed to generate NPP in forests, with temperature as a major factor affecting basic photosynthetic and respiration rates.

Leaf area index (a dimensionless quantity the represents the green leaf area per unit ground surface area) is an important measure of potential productivity because it indicates the extent of site occupation by leaves with respect to light interception. Leaf area index is also affected by the way in which plants allocate NPP between their different organs. As with leaf area, this carbon allocation is influenced by the availability of water, light, and nutrients. NPP is allocated to the root system or to leaf and stem growth in response to which resources are in shortest supply: soil nutrients and water versus energy and carbon (Figure 4.1). Changes in allocation are thought to represent the plant´s attempt to maintain optimum ratios between carbon and other nutrients, and between leaf area and the supply of light, moisture and nutrients to that leaf area.

Leaf area index appears to affect NPP more than photosynthetic efficiency, though both are obviously important. High values for accumulated biomass are associated with high leaf areas but the efficiency with which the biomass is produced does not show a linear relationship to leaf area index. As leaf area increases, an increasing proportion of the tree biomass is under deeper shade, and therefore contributes less and less to the net production of biomass from photosynthesis. Leaf area index is functionally related to the cross sectional area of sapwood. Sapwood is the component of tree stems that conducts water and nutrients to the foliage, and therefore is functionally related to leaf area. Basal area (or its surrogate, the number of trees in a stand) is the basic variable that can be manipulated by forest management. Therefore, it is important to understand how forest management affects the different factors that intervene in biomass production by photosynthesis.

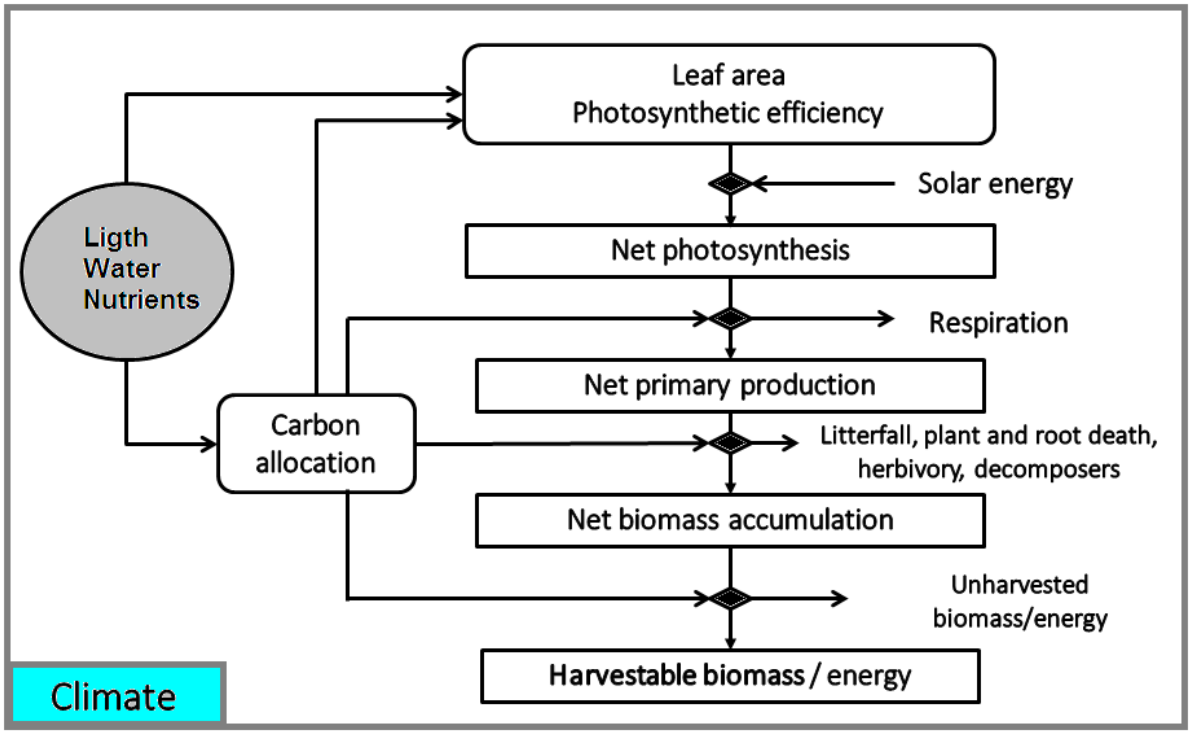

Figure 4.1 The major determinants of economic production (yield) in a forest ecosystem within a particular climate regime. The availability of site resources (light, water, resources) is critically important, both directly and indirectly, through their effect on the allocation of net photosynthesis (Modified with permission from the original by J.P. Kimmins).

Light

Photosynthesis is a process in which the rate of fixation of CO_2 and the capture of solar energy is dependent largely on light intensity. The rate of photosynthesis increases rapidly with light intensity (if other factors are not limiting), but initially there is no net CO_2 fixation, (and therefore no biomass production) because the rate of CO_2 generated and lost through respiration is greater than the rate of CO_2 fixation. As light intensity continues to increase, a point is reached at which respiratory losses are balanced by photosynthesis gains. This light intensity is called the compensation point. Above it, the rate of photosynthesis continues to increase rapidly with increasing light intensity, but this relationship is not sustained. With continued increases in light, the rate of increase in photosynthesis diminishes until the saturation point is reached, beyond which further increases in light intensity result in little or no further increase in net CO_2 fixation rate. At very high light intensities, net fixation may drop because of damage to the photosynthetic apparatus, or for other reasons (Figure 4.2).

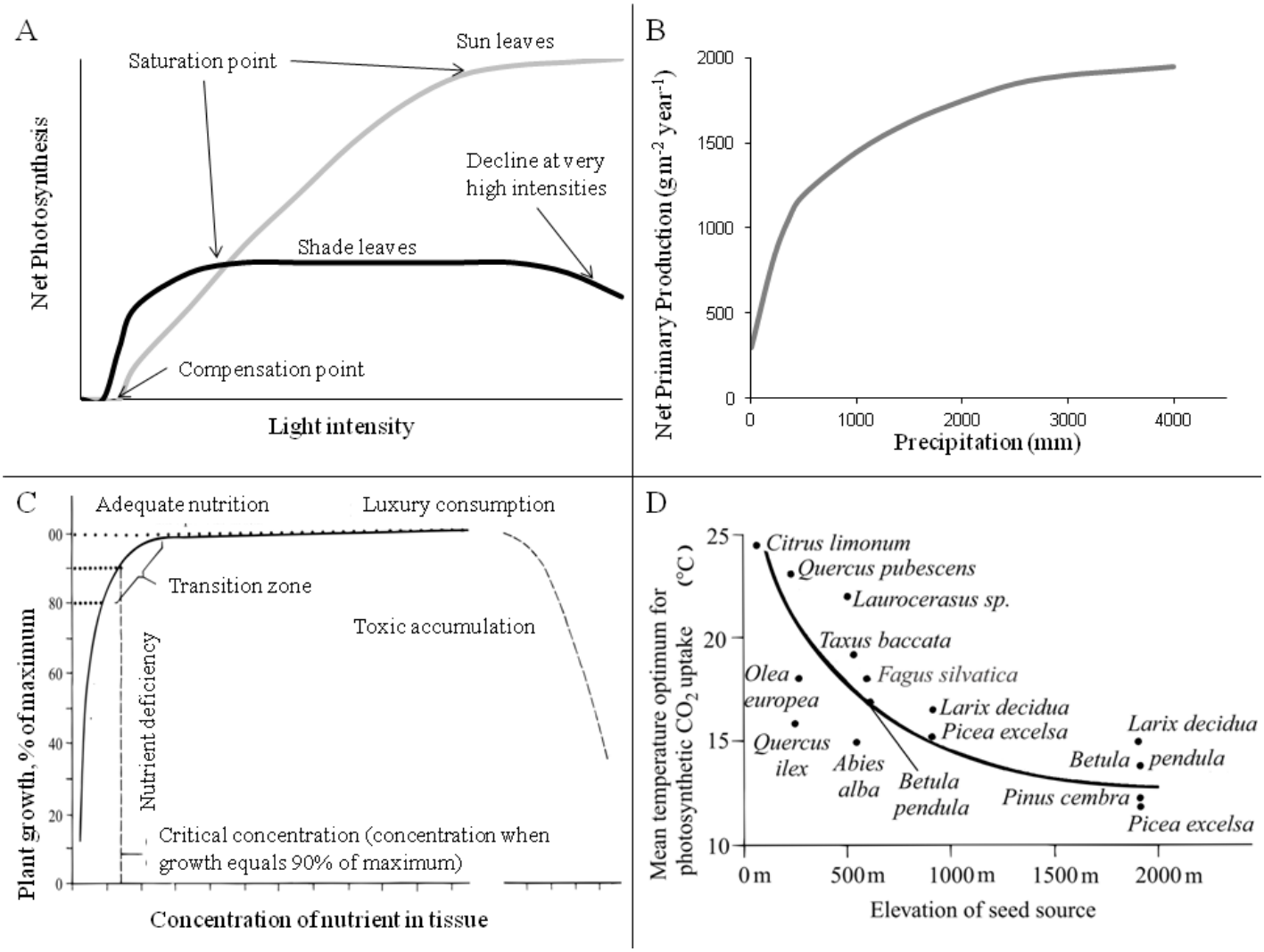

Figure 4.2 Relationship between tree productivity and main growth limiting factors: A) light: B) water (annual precipitation, modified from Reichle (1981): C) nutrients (modified from Ulrich and Hill 1967); and D) temperature (modified from Pisek *et al*. (1969).

Some species can survive in more shaded conditions than others because their leaves can photosynthesize enough at lower light intensities to at least offset respiratory losses. Usually, more light is needed for whole trees than for shrubs and herbs, since the leaves must produce enough carbohydrates to keep stems, branches, and roots alive. The architecture, spatial arrangement of leaves, and respiration rates of stems, branches, and roots are all important in allowing some species to survive at lower light intensities than others. Such species are described as shade-tolerant. The extra sunlight utilized by shade-tolerant species contributes little to growth, although it may enable the species to survive in understory, shaded conditions (Oliver and Larson, 1996).

Forest management can influence light efficiency to enhance biomass production in a stand. For example, having two species coexisting, one fast-growing and shade-intolerant (such as trembling aspen, *Populus tremuloides*), can create an environment where a more valuable but slower-growing, shade-tolerant species (such as white spruce, *Picea glauca*) can survive (Fig. 4.3). Later, when the aspen is harvested at maturity,

the spruce is released and then grows in direct sunlight until it is ready for harvest (Welham *et al*. 2002). Other management practices such as thinning can influence light use efficiency and increase stand leaf area by removing the trees which are occluded in the lower parts of the canopy and therefore getting access to less light. Due to this relationship between light and productivity, light has been used as the main factor driving some forest growth models, such as SORTIE (Pacala *et al*. 1996).

Figure 4.3 Tembling aspen (*Populus tremuloides*) overstorey with an understory of slower-growing white spruce (*Picea glauca*). Dease Lake, British Columbia, Canada.

Atmospheric gases (O_2 and CO_2)

Trees require oxygen to obtain energy from respiration. Oxygen is absorbed through bark lenticels, leaves, buds, and roots. Oxygen is usually not a limiting factor for tree production, except when it is not available for roots, as in water-logged soils. Some species, such as tupelo (*Nyssa sylvatica*), bald cypress (*Taxodium distichum*) or mangroves can survive for several years in standing water, using a physiological method to move oxygen from stems and leaves to the roots (Oliver and Larson, 1996).

Figure 4.4 Floodplain forest dominated by *Taxodium distichum* in the Apalachicola National Forest, Florida, USA. The heght of the water level is indicated by the black marks on the stems. The spikes in the foreground are pneumatophores, modified roots that rise above the water-logged ground to enable the trees to breathe.

Carbon dioxide is absorbed by plants and combined with water to create organic compounds through photosynthesis. Entrance of CO_2 into leaves and its subsequent fixation depend on the concentration gradient between the exterior and the interior of the leaf. This gradient will be higher if atmospheric CO_2 concentrations rise above normal levels, such as in greenhouses or through fossil fuel emissions. CO_2 movement from the exterior to the interior of the leaf needs to overcome stomatal resistance, which is related to the degree to which stomata are open. This resistance is high in species with sclerotic leaves (thick and hard, usually adapted to dry environments). Even with numerous stomata, these species do not open the stomata very much (Terradas 2001). The degree to which the stomata are open depends on the turgor pressure differential between the guard cells of the stomata and the surrounding epidermis cells. Turgor depends on ionic concentrations inside the cells, and any process that affects this concentration will result in changes to the flow of CO_2. This process is often related to the availability of water.

In a future atmosphere rich in CO_2, plants may become more productive due to the greater availability of carbon for photosynthesis. Historical increases in tree growth in relation to rising CO_2 concentrations within the 20th century have been identified (Graybill and Idso, 1993). However, this 'fertilization' effect will only be maintained if there are no other limiting factors. For example, soil nutrient levels will need to be sufficient to support increased tree growth.

Water

Water is the main resource that limits vegetation growth and survival in terrestrial ecosystems. Water is not only used in photosynthesis, but it acts as the medium in which all life-related chemical processes occur. Water also acts as the transport system permitting nutrient uptake from the soil, and in moving oxygen and metabolites around. Total biomass and NPP are often proportional to water availability. Water can be the limiting factor in many forests, from boreal to tropical ecosystems.

The production of biomass per unit of water used is a measure of how effectively plants use water, and is called Water Use Efficiency (WUE). WUE has been investigated in a wide variety of plants. Many tree features (type of leaves, tree architecture, seasonal growth, etc.) have evolved to maximize WUE. As a consequence, large variations in WUE have been reported between species, sites of different productivity, and under different climatic conditions.

Plants obtain water primarily from the soil through the fine roots. To take up water, plants exert tension through evapotranspiration and are able to draw any water from the soil that is not strongly adhered to soil particles. If plant tension is greater than the attraction tension (matric potential) of the soil, water moves from the soil into the plant. Trees vary in their ability to extract water from the soil and endure conditions of high soil water tensions without injury. By opening or closing stomata, trees have the ability to regulate water flows in relation to availability. Most tree growth occurs at soil water tensions of less than –1 MPa. There is a direct relationship among the energy, water and carbon balances in the leaves, which are also affected by temperature. Any change in temperature changes the water vapour deficit in the air, and changes the water tension in the plant, affecting evapotranspiration.

Tree species can use different strategies to endure periods of low water tension (low water availability). The stomata in the leaves can be closed to avoid drought, shutting off transpiration and maintaining high internal moisture levels, but at a cost of impairing photosynthesis. This strategy is typical from species living in arid sites or in sites with seasonal aridity, such as Mediterranean ecosystems or the dry tropics. In these areas, the dry season is usually a time of dormancy for trees.

Excess water can also have negative impact on tree productivity. Flooded soils prevent oxygen from reaching roots. Soil water can also contain dissolved salts, thereby increasing water tension. This makes it more difficult to absorb the water, effectively reducing water availability for plants.

Forest management can influence water availability in different ways. Irrigation can substantially increase productivity by increasing the standing leaf area (Campoe *et al*. 2013). It is also possible to control the number of plants and tree at a site that are actively removing water from the soil. By reducing tree density, evapotranspiration can be reduced as well as rainfall interception, increasing soil water availability (Bréda *et al*. 1995). For this reason, thinning can also increase runoff. In semi-arid environments with high solar radiation levels, thinning can increase light incidence to the soil surface, increasing soil temperature and therefore evaporative losses. In saturated soils, forest drainage (ditching) can reduce water content and increase air (and oxygen) content in the soil. However, this practice can have important environmental consequences, such as changes in biodiversity or impacts on forest streams.

Mineral nutrients

A large number of chemical elements can be found in plants. Many occur at very low concentrations (parts per billion) and have no known role in plant metabolism. However, other elements have important roles in plant metabolism, such as calcium (cell walls), nitrogen or sulphur (proteins and nucleic acids), phosphorus (energy-transport molecules), or enzymes controlling chemical reactions (magnesium, potassium, manganese, etc.). Only a few (N, P, K, Ca, Mg, Mn) are found at concentrations that can be expressed as percentages by weight of plant substance.

Nutrients are usually dissolved in soil pore water (soil solution). The fraction of available nutrients is actually only a small part of the nutrients in the soil. A large fraction is adsorbed onto soil colloids (mineral and organic particles in the soil with electric charges). Plants need to exchange ions with the soil to uptake nutrients. To keep their osmotic equilibrium, plants release protons (H^+) when uptaking ammonia (NH_4^+) or carbonate (HCO_3^-) when taking up nitrate (NO_3^-).

Most soil nutrients are not in soluble form, though solubility depends on pH. Most of the nutrients needed in higher quantities by trees (macronutrients) exhibit maximum solubility at pH values between 6.5 and 7.5, although metallic ions are generally less available above pH 7. Soil pH is not the only factor determining nutrient availability, however. Clay minerals and organic soil matter are rich in electrical charges, and therefore they have the capacity to store cations. Therefore, soil texture (the relative proportions of clay, sand or silt) and the amount of organic matter in the soil define the cation exchange capacity (see Chapter 6). How full or empty that pool is depends on the rates of nutrient inputs and outputs. Such flows include the decomposition of organic matter that releases (or sequesters) nutrients into the soil, wet and dry atmospheric deposition, biological fixation, biochemical transformations (volatilization, nitrification, ammonification and other transformations of soil nitrogen), runoff, erosion, leaching, or combustion of forest soils. These processes define the status of the soil with respect to its ability to supply the nutrients essential to plant growth, or in other words, soil fertility (Soil Science Society of America, 1973).

Once inside the tree, most nutrients are concentrated in the physiologically active organs: leaves, phloem (interior side of the bark), buds, fine roots, and reproductive organs. Trees can resorb some nutrients from foliage before it falls to the ground, reducing demand from the soil. This done through the removal of amino acids from the leaves; the amino acids are produced by the breakdown of chlorophyll a and b, other ligands and apoprotein. At the same time, an abscission layer is forming near the junction of the leaf and the stem, and this restricts the flow of minerals into the leaf, which is actually why the amount of new chlorophyll being produced declines. The loss of the green chlorophyll pigment reveals yellow and orange pigments that were previously masked (xanthophylls and carotenoids, respectively) and some trees start creating red and purple pigments (anthocyanins). Others accumulate tannins, giving the leaves a brown coloration. The rate and intensity of these processes vary geographically, being most apparent in northeast North America and northeast Asia. Larches (*Larix* sp.) can also create vivid fall coloration, but similar patterns are generally not seen in deciduous trees found in seasonally dry tropical and sub-tropical climates.

Figure 4.5 Fall colours, Quebec, Canada.

Figure 4.6 Fall colours in Graubünden, Switzerland. Only the European larch (*Larix decidua*) have changed colour, woth the other conifers being evergreen.

Forest management can influence nutrient availability in many different ways. Any practice that alters the capacity of the soil to retain nutrients, or the size of the nutrient pools will affect availability. Fertilization in forest plantations can increase nutrient availability and therefore tree productivity. On the other hand, slash burning can volatilize nutrients from harvest residues, particularly nitrogen, phosphorous and sulphur. Tree thinning and harvesting, when removing only stems, exports only small quantities of nutrients from the site as their concentrations in stemwood are small. However, whole tree harvesting that removes foliage, especially when combined with short rotations, can export an important part of the nutrients in the vegetation, leading to a drop in soil fertility. Some examples of yield declines from conifer plantations can be found in North America (Johnson, 1992), Oceania (Smethdrust and Nambiar, 1990), Europe (Blanco *et al*. 2005) and Asia (Bi *et al*. 2007). This productivity drop can be relatively fast if slash burning or soil erosion also occur, and depending on the circumstances can reduce soil fertility for very long periods (Blanco, 2012). Forest management can also affect other important processes such as erosion, runoff, and soil leaching (see Chapter 6). If such processes are in constant action through time they can also lead to losses of nutrient availability and therefore of soil fertility and stand production. Nutrient availability has been used as the main growth limiting factor in forest growth models such as FORECAST (Kimmins *et al*. 1999).

Temperature

Temperature regulates the speed and activity of chemical reactions. Active metabolic processes for many organisms are restricted to temperatures between 0°C (the point at which water freezes) and 55°C. The respiration rate increases steadily through this range, although the rate of change varies among species. Gross photosynthesis, on the other hand, increases rapidly from the freezing point to a relatively constant "plateau" between 8 to 18°C, depending on species. Any further increase in temperature will cause a decrease in net photosynthesis (gross photosynthesis minus respiration) and therefore in tree productivity and growth. Outside this range, trees use different mechanisms to survive temperature extremes. Some species develop deciduous leaves or small and hard evergreen leaves, other species generate thick and isolating bark, and most species close the stomata.

Temperature varies considerably in different parts of a plant. Roots normally assume the temperature of the soil around them. In regions away from the equator root temperature is lower than shoot temperature in the summer but may be higher in the winter. Shaded stems approximate air temperature under the canopy, although the insulating properties of bark cause stem temperatures to lag behind those of the air. Leaves may have temperatures higher, lower or the same as the surrounding air. Thin leaves with high transpiration rates can be as much as 15°C cooler than air in summer, whereas thick leaves may be up to 30°C warmer than surrounding air temperature.

Temperature in forests depends mostly on geo-topographic conditions. Slope, aspect, altitude, and latitude affect the amount of solar radiation reaching the forest and influencing temperature. The topographic situation (valley bottom, mountain side or top, leeward side of the dominant winds, etc.) influences air movement and therefore air temperature. As forest management will have very little impact on these conditions, the main management decision related to temperature is to plant species that can survive at the minimum and maximum temperatures of each site, not only the historical ones, but also the ones that are expected in a future under climate change (Wang *et al*. 2012).

Removing trees through harvesting or thinning changes the amount of solar radiation reaching the soil surface. Storm damage may create similar conditions, especially if the downed trees are salvaged. As a result, forest management can have important impacts on microclimate, affecting soil and soil surface temperatures. This has consequences for soil organisms such as decomposers and small plants. It can also impact the reforestation of sites, with the microclimate being so changed in some situations that the re-establishment of trees becomes very difficult.

Figure 4.7 This slope near Dissentis in Switzerland lost its foresr cover due to an extreme windstorm. The downed wood was salvaged, but after this, regeneration has proved to be very difficult, likely because of changes in the microclimate.

In boreal and alpine forests, increasing soil temperature usually produces an increase in decomposing rates, as decomposing activity is stimulated. However, in temperate and arid tropical forests, increasing soil temperatures may reduce decomposition due to higher evapotranspiration and less moisture available for decomposers (Prescott, 2010). In new plantations, seedlings can also suffer from heat stress as they are close to the soil surface, where the highest temperatures are reached and there is little bark to protect the cambium. This can be prevented by shading all or part of the seedlings, artificially or with nursery crops (Helgerson, 1990). Seedlings and understory can also have a sudden temperature stress if the overstorey is removed and solar radiation to the soil increases. Temperature is the main growth limiting factors in some forest growth models, such as 3-PG (Landsberg and Waring, 1997).

Ecosystem composition, trophic relationships and food webs.

Ecosystem productivity increases as ecosystem composition becomes more diverse until reaching a maximum at medium diversities. However, productivity decreases if diversity continues increasing. No general model has been derived yet that would explain this relationship. There are several hypotheses to explain this relationship between species diversity and site productivity.

One hypothesis states that species diversity is related to micro-site diversity (Rozenzweig and Abramsky, 1993). In theoretical ecology it is well-known that one ecological niche can carry only one species. This theory says that average sites have more niches than very poor or very rich sites. For example, in poor sites (cold, dry, or nutrient scarce), all temperature, moisture or nutrient availabilities have low values. This is the result of a unique combination of factors that represent a specific site with very low productivity. Similarly, rich sites (warm, moist, and nutrient rich) are also the result of a unique combination of factors. However, sites of average productivity can be reached with a great number of combinations of site factors. Each combination represents a specific niche, which can carry a specific community and hence also have higher species diversity. According to this theory, site diversity is maximum on average sites, and as a consequence species diversity is also maximum on average sites. This theory supposes that productivity is a consequence of resources being used in a more complete way when diversity is high, as different species will be using different portions of the available resources (Terradas, 2001).

A second hypothesis is based on the theory of the limiting factor (Rozenzweig and Abramsky, 1993). This theory states that when site productivity is high all species have the potential to survive. However, a large number of species on the same site leads to strong competition resulting in productivity reductions. This theory assumes that diversity is a consequence of high productivity and inter-specific competition. Hence, low diversity can be caused by the strong competition of the most competitive and dominant species, which suppresses other species. In forest communities, this phenomenon is easily observed when one dominant tree species dominates the canopy, uses most of the site resources and suppresses other tree and plant species, reducing species diversity over time.

In forestry applications, the relationship between ecosystem productivity and composition is closely related to the higher production observed in mixed forests compared to monocultures (Pretzsch *et al*. 2012). This has become an important issue because of pressure to adopt what are viewed as more natural forms of forestry (near-to-nature forestry), and which eschew exotic species and monocultures. In both planted and natural forests, this approach to management results in greater areas of uneven-aged and heterogeneous forest stands, which complicate the use of traditional growth and yield models. Some efforts have been made to create models that would enable the determination of volumes of several mixture types and forms, such as the SILVA model (Pretzsch, 2010).

Figure 4.8 Mixed species plantation of Schrenk spruce (*Picea shrenkiana* var. *crassifolia*), Chinese red pine (*Pinus tabuliformis*) and Hebei poplar (*Populus tomentosa*), Xining, Qinghai Province, China.

Trophic relationships and food webs

Forest ecosystem productivity and diversity does not only take into account plant productivity, but also the productivity of herbivores, carnivores and saprotrophs (decomposers). They use plant production (NPP) as an energy source, but they can also be the source of energy for other organisms. Biomass (and its associated energy and nutrients) flows through the ecosystem following the food (trophic) chains. However, the same organism can be part of different trophic chains as it can feed on or be food for different organisms. Trophic chains are then organized in trophic webs at ecosystem level.

Understanding how energy and nutrients flow through the different parts of the forest ecosystem is important when developing sustainable forest management plans. Forest management generally involves the production of a crop, whether timber, wildlife, mushrooms, berries, or other materials. Many management practices influence energy accumulated in the forest biomass. For example, maximum aboveground biomass values have been reported to reach up to 422 Mg ha^{-1} and 415 Mg ha^{-1} in mature temperate and tropical forests, respectively, but up to 3,461 Mg ha^{-1} in old growth forests in coastal conifers in California (Kimmins, 2004). Converted to energy at 4,000 cal g^{-1}, the energy contained in this aboveground biomass could equal to 2,000 Mg of coal. This energy could be used for local heat or even

electricity production in biomass power plants, but then the energy contained in the forest biomass is not available to flow through the trophic webs as it would leave the ecosystem through harvesting.

When a forest is harvested there are several important changes in the distribution of energy and how it flows in the ecosystem. First, by removing the overstorey canopy, most of the energy entering the trophic web is eliminated, and photosynthesis is temporarily carried on only by understory vegetation. Second, there is a potential increase in the energy flow through the detritus food web. Depending on the type of harvesting (stem-only, whole-tree, or complete-tree), variable quantities of tree biomass (slash) are deposited on the ground. After clearcutting there is characteristically a period of rapid reduction in the thickness and biomass of the forest floor, because biomass inputs to the forest floor through litterfall are greatly reduced. Increased detritus energy flow after harvesting is the combined result of both increases in the quantity of decomposable organic matter and changes in the condition of the forest floor. Summer daytime temperatures at the forest floor increase after logging. Such changes can enhance decomposer activity in temperature-limited boreal, alpine and cool-temperate forests, but it can inhibit decomposers in warm-temperate and Mediterranean forests, as warmer soils are usually also drier (Blanco *et al*. 2011). In addition, removing trees also causes the breakdown of mycorrhizal relationships, a reduction in the mycorrhizal fungi biomass, and an ncrease of free-living saprotrophs.

Figure 4.9 Chinese fir (*Cunninghamia lanceolata*) seedling, Nanping County, Fujian, China. In growing this species, the organic matter from the previous stand is usally removed, a practice that may reduce the allelochemical content of the litter.

Loss of forest floor biomass and depth after clearcutting can have several effects on the ecosystem. Forest floor water and nutrient storage capacity may be reduced, which can be undesirable in hot, dry climates and infertile sites, but desirable in cold, humid mineral soils. On sites where the forest floor has adverse chemical properties (too little N in the litter, allelochemicals present, etc.), or where deep layers of low bulk density material pose problems for regeneration (because it dries rapidly in summer), the reduction in depth may favour the reestablishment of a tree crop. As the pioneer plant community re-establishes a foliage canopy, the entry of energy into the ecosystem is gradually restored. Litterfall inputs to the forest floor gradually increase, much of which decomposes rapidly. The development of summer shading increases the moisture levels in the slash and forest floor, which promotes decomposition. However, as the tree canopy develops and succession proceeds, the type of litterfall changes, mycorrhizal fungi begin to dominate the soil microflora, and decomposition rates slowly return to pre-logging values.

Accompanying the post-harvesting increase in detritus food web energy flow there is a reduction in energy flowing through the grazing food web. The reduction intensity is proportional to the reduction in leaf biomass available for herbivores. The invasion of the stand by pioneer herbs and shrubs after harvesting rapidly re-establishes the grazing food web, often at a higher level of energy flow than before logging. This is due to the greater physical accessibility, palatability, and nutritive value of the understory in comparison to the mature tree canopy. This can result in more diverse, abundant, and productive animal communities in harvested stands than in the original uncut forest, as long as the wildlife requirements for shelter and winter range are satisfied (Welham *et al*. 2012).

Figure 4.10 The moose (*Alces alces*) is one of a number of species of ungulate that can benefit from the improved food supply that occurs after a disturbance.

Productivity of timber and non-timber resources

Producing both timber and non-timber forest products (NTFP) supposes that ecosystem productivity is used to generate both type of values. Each value is associated with different tropic webs. As a consequence, implementing forest management to favour one forest product could reduce the energy and materials available to produce another product. For example, reducing tree cover to increase understory production would increase production of game animals by diverting energy into the herbivore trophic web. However, it also lowers the potential for timber production. Similarly, favouring forest floor development could increase production of mushrooms (fruiting bodies of saprotrophic fungus in the decomposers trophic web), but reducing nutrient availability for tree production as nutrients get sequestered in the litter layer.

Maintaining forest structure associated with NTFPs production is generally acknowledged as being positive, contributing to forest environmental functions like carbon storage, nutrient cycling, erosion control and hydrological regulation. Moreover, forests managed for NTFP production can retain large amounts of plant and animal biodiversity (Michon and de Foresta, 1997). On the other hand, NTFP harvesting results in direct and indirect pressures on the forest, due to competition between humans and animals for some forest foods (Boot and Gullison, 1995). There are consequently concerns about just how benign the harvesting of NTFPs is, and whether these arguments have been over-stated. NTFP depletion or removal can rapidly influence such forest characteristics as composition and structure of vegetation (Arnold and Ruiz-Pérez, 2001). For example, extraction of bark can lead to the death of the tree, while the harvesting of fruits and flowers may have negative results for the reproduction of the population. Some species are better able to sustain continuous off-take than others. In the case of vegetation, those species exhibiting abundant and frequent regeneration and rapid growth will prevail (Peters, 1994). Likewise, rodents, ungulates and other animals that have broad niches and prolific reproductive strategies are more able to stand heavy hunting (Fa *et al*. 1995).

As it can be seen in Table 4.1, most of the measures that benefit biodiversity, impact negatively on tree productivity, both at the stand and the landscape level. However, at the landscape level, it is important to separate between effects that impact on the tree production per unit of forest land and on the overall landscape. The synergies and trade-offs between biodiversity and productivity at the landscape level depend largely on the forest policy context. If plantation establishment is directly related to and dependent on the area of native forests set aside for conservation, there can be strong synergistic effects (Paquette and Messier 2010, see also the section below on the TRIAD approach to forest management).

As with any form of natural resource management, there is no form of plantation management that can provide a maximum of all timber and non-timber products. It is simply not possible to maximize wood production, carbon sequestration, conservation of biodiversity, and social and cultural benefits in the same forest stand (Bauhus *et al*. 2010), and attempts to do so will always result in one or more values suffering while others benefit.

Table 4.1. Estimated trade-offs between the effects of certain management options on selected ecosystem goods and services (Modified from Bauhus *et al*. 2010).

Management options	**Tree productivity**	**Understory productivity**	**Biodiversity**	**Carbon**	**Water**	**Amenity values**
Stand level						
Structural retention	-	(-)	+	?	+	+
Use of native species	-	?	+	(-)	(+)	+
Mixed-species stands	+	-	+	+	-	+
Long rotations	(-)	-	+	?	+	+
Short rotations	(+)	+	-	?	-	-
Thinning	0	+	+	-	+	(+)
Whole-tree harvesting	(+)	+	-	-	+	-
Site preparation	+	-	-	?	?	-
Herbicides and fertilizer	+	-	-	?	-	-
Landscape level						
Riparian buffers (of native vegetation)	-	+	+	(+)	+	+
Retaining patches of native vegetation	-	+	+	(+)	+	+
Connectivity between plantations and native forests	0	(+)	+	0	0	+
Maintaining landscape heterogeneity (different land-use types, special places, etc.)	-	(+)	+	?	+	+

Note: + = positive effects, - = negative effects, 0 = neutral effect, ? = unknown or uncertain effects, brackets indicate that the effect may not be so clearly positive or negative depending on other factors not captured here.

Changes in site productivity as they relate to semi-natural forests and plantations

Plantations are forests established from the intentional planting or sowing of propagules (seed, seedlings, or cuttings) to generate an even-aged stand, with the aim of producing particular forest products, or for protective purposes (Schuck *et al*. 2002). Geometric plant spacing is a classic feature of these stands, in addition to artificial regeneration with either native or non-native species. Intensive management techniques and protection measures are employed initially, and sometimes on an ongoing basis, to maintain growth trajectories and stand composition. Stands established as plantations but which have been without intensive management for a significant period of time are likely to revert to a semi-natural condition. Semi-natural forests include tree species that occur naturally in the stands, either from ingress or through artificial assisted regeneration. Hence, they show similarities to natural forests in terms of age class distribution, composition, and structure.

Conversion of natural forests to plantations can occur after harvesting (live and salvage logging), following a stand-replacing fire, or when the existing stand is killed by pathogens or a severe climatic event, such as a drought. Regardless of the disturbance type, site preparation is undertaken in most cases to improve planting conditions and ensure successful establishment of the crop species. This can include slash removal, prescribed burning, mechanical treatments, and in some cases, drainage and irrigation (Smith, 1962). Natural forests build up considerable stocks of dead organic matter and propagule banks over generations (seed stock, for example). This historical legacy can confer substantial resilience to disturbance in terms of the ability of a system to return to equilibrium stability (see Holling and Gunderson 2002) following a perturbation event. Productivity of the crop in the next rotation is therefore likely to be at least equivalent to the prior cohort, assuming disturbance is not too severe (see Bi *et al*. 2007). Productivity could even be enhanced if a previously limiting factor can be mitigated through management (i.e. insufficient stocking, nutrient availability, poor drainage). Conversely, tree growth could be reduced if the disturbance event and/or site preparation significantly impair key processes driving ecosystem recovery.

A fundamental tenet of sustainable forest management is to maintain forest capacity to provide a characteristic suite of ecosystem goods and services. Although disturbance alters structure, composition, and function, given sufficient time a forest will restore the original balance in these ecosystem attributes. A pattern of non-declining change is thus sustained over the long-term as the disturbance-renewal cycle is repeated. A characteristic of many plantations, however, is that in an effort to generate higher economic returns, the renewal time between harvesting events (i.e., the rotation age) is often much reduced over what occurs in the natural forest. If the rotation age is too short, not all ecosystem attributes will be completely restored leading to an eventual decline in productivity. One example is dead organic matter (DOM). In northern coniferous forests, DOM is an important source of nutrient inputs (see Laiho and Prescott, 2004), and long-term nutrient storage and release. Depletion of DOM stocks can occur because branches and foliage are often separated from the log bole at roadside, where they are then burned in slash piles. As part of site preparation, DOM is often cleared from the site to facilitate planting. Finally, shorter rotation times interrupt the mortality patterns associated with stand development in natural forests, which does not allow for sufficient re-accumulation of DOM (Harmon *et al*. 1986). As noted above, because of

inherent resilience, the impacts associated with the degradation of DOM stocks may not become apparent until several rotations later.

Figure 4.11 Slash derived from harvesting piled up rather than distributed through the forest, western Tasmania, Australia.

Maintenance of both forest area and forest quality

Sustainable forest management needs to provide the resources that society is demanding from the forests, but in a way that both current and future demands can be met. This requires the maintenance of both forest area and productivity (forest quality).

Maintaining forest area depends largely on forest policies, forest types, and how nutrients, energy and water are circulated in the ecosystem. For example, tropical forests growing on extremely nutrient-poor soils, such as weathered soils in the Amazon basin and in northern Australia, or the peat forests of Sumatra, are of low productivity. These low-productivity forests lack the species diversity, multilayered canopies, and tree heights associated with tropical forests growing in more fertile sites, such as alluvial soils in the floodplains of tropical rivers, or young volcanic soils (Kimmins, 1999). Where forests on nutrient-poor, low quality sites are cleared for agriculture or other land uses, soil tends to degrade very rapidly, and such areas are usually abandoned within a few years. If they are abandoned before soil fertility or soil structure has been severely damaged, an impoverished secondary forest will rapidly invade. Over time, trophic webs and

energy flows will be gradually restored, and the original forest could substitute the secondary forest over time. This is the usual course of events under the traditional practice of shifting cultivation.

Figure 4.12 Forest cleared during shifting cultivation, Crocker Mountains, Sabah, Malaysia.

On the other hand, if the soil is used for longer times and to produce more intensive harvests, the soil becomes too impoverished to allow the development of secondary forest. Pioneer grass or shrub species with the ability to survive in very poor sites can dominate the area and prevent trees from establishing. Burning the site may remove the understory and improve site conditions temporarily as some of the nutrients stored in the plants are released into the soil. Generally, however the result is a loss of soil organic matter and nutrients (Bi *et al*. 2007). This is because most of the nutrient pools in low-quality tropical forests are in the vegetation. Once the plants are removed, this pool is lost and nutrients become more limiting, even if water, light and temperature are favourable. The resulting low site quality forces the farmers and loggers to clear more forest land, and deforestation then spreads. Forests on fertile, high-quality sites, in contrast, are much more resilient, and have soils with appreciable nutrient reserves. Such soils are capable of supporting sustainable forestry if managed in a way that conserves their soil organic matter, nutrient reserves, structure and avoids erosion. Intensive forestry in plantations established in such sites is possible, if the site quality is preserved.

Figure 4.13 A plantation of hybrid Eucalyptus (*Eucalyptus urophylla* x *grandis*) on Hainan Island in southern China. The trees, which are 30 months old, have an average height of 15 m and average DBH of 12 cm. The trees will be harvested for pulp at an age of ca. 36 months. The spacing is 4 m x 1.67 m. Great care will be needed on this site to ensure that productivity is maintained.

In temperate and boreal forests, the same considerations for sustainable ecosystem management apply. To preserve the existing forest area, productivity should be maintained through time so no new areas need to be brought under management. It is therefore necessary to avoid overexploiting site resources. In many temperate forests, and most boreal sites, soils are relatively young and mineral nutrient pools are usually adequate to support tree productivity. Species diversity is lower in temperate and boreal forests than in the tropics. Management practices that create a mosaic of forest and non-forest landscapes can increase species diversity at landscape scales. In temperate regions of Europe, the abandonment of low-productive agriculture and pasture lands has led to an expansion of forest area during the last decades, thereby contributing to the landscape mosaic.

In terms of forest quality, practices used to increase short-term tree productivity such as short rotations, whole tree harvesting, and intensive site preparation, can result in nutrient and organic matter exports exceeding natural inputs. This will eventually lower site quality and cause a reduction in productivity. This decline is often cumulative and non-linear across rotations. This phenomenon has been documented in conifer plantations around the world (Bi *et al*. 2007). Natural nutrient inputs (by atmospheric deposition, biological fixation, mineral weathering, etc.) can be supplemented by fertilization. To maintain growth rates, fertilizer doses usually need to be increased every rotation. However, increasing the amount of

fertilizer can have environmental consequences, such as increased N leaching to watercourses and groundwater (Wei *et al*. 2012).

Managing the forest stand to grow under longer rotations enables the development of biological structures such as snags, logs, canopy structure, etc., which mimic some features of natural forests and could even reach some of the attributes of old growth forests, provided that the rotation is long enough (Franklin *et al*. 2002).

A sustainable basis for the intensification of production

Advantages and disadvantages

As discussed in Chapter 1, the intensive culture of woody crops is an activity dating back many centuries. The modern concept of the short rotation woody crop (SRWC) can be defined as a silvicultural system based upon short clear-felling cycles that employs intensive cultural techniques such as fertilization, irrigation and weed control, and utilizing genetically selected planting material (Drew *et al*. 1987). A key feature of successful SRWC culture is density regulation; plantations are typically established at densities well exceeding 10,000 stems ha^{-1} to minimize weed competition and ensure that site resources are fully utilized. Dickmann (2006) added the proviso that SRWC systems often rely on coppicing, but this is only appropriate for some species. Extensive selection and biotechnology programs have also played a critical role in producing high yielding tree varieties and efficient clonal propagation methods. SRWC systems are used as sources of fuel, bioenergy feedstock, bioremediation, and to promote carbon sequestration.

For obvious reasons, intensive production has the benefit of generating the desired products or objective in the shortest time possible. Establishing a new plantation is relatively easy because many species can be propagated asexually, or seed can be quickly produced in large amounts (see Dickmann, 2006). Following harvest, coppice regeneration often ensures vigorous regeneration and biomass accumulation, although clonal vigour often declines over subsequent rotations and a new plantation must be re-established. Many eucalypts regenerate freely through coppicing. Jarrah (*Eucalyptus marginata*) is particularly recognized for this ability, but some eucalypt species important for timber, including mountain ash (*E. regnans*), alpine ash (*E. delegatensis*) and rainbopw gum (*E. deglupta*) do not regenerate in this way. There is evidence of improvements in soil organic matter, structure, and fauna when formerly agricultural sites are converted to plantation forestry (Makeschin, 1994a, b).

Challenges to realizing its potential and then sustaining intensive production can be grouped into two broad categories, issues with plantation performance and site-related features (see Makeschin, 1999). Weed competition is a major factor limiting plantation establishment and growth. Effective weed control depends on intensive site cultivation usually in combination with herbicides. Fertilization is often required to promote early growth and then sustain productivity over the long-term (both within and across rotations). This can introduce potential issues with nutrient leaching and runoff, thereby impacting ground and surface water quality. As with any monoculture, pests and diseases can be problematic. Protection of young seedlings from herbivore browsing may be a necessity. Insect and fungal pest control often requires the

application of chemical pesticides and fungicides. Selection of disease-resistant clones and materials well-suited to prevailing site and climate conditions are prerequisites to avoiding problems and realizing the sustained yield potential.

Site-related features include the inherent characteristics of a given site (biodiversity, soil), and how repeated cropping impacts soil quality. Experience has demonstrated that the potential of intensive production systems can best be realized when sites possess adequate nutrient and moisture regimes at the outset. As discussed in Chapter 6, soils that are either poorly or excessively drained, infertile, stony, shallow, highly acid or alkaline in pH, or degraded through erosion, compaction, or salinization simply will not support the productivity needed to justify an investment in intensive forestry. Wet soils prohibit the use of mechanized equipment because of soil compaction, while steep slopes introduce the risk of soil erosion. Conversion from a natural forest to intensively managed single-species plantations results in a severe reduction in biodiversity. This is not only in terms of overstory composition but also in the understory, whose abundance must be severely controlled to eliminate competitive effects. It is likely that the soil biota is also affected also (Makeschin 1999a). In the long-term, intensive plantation management will likely lead to losses in soil organic matter, with associated reductions in available nutrients. This will require the use of fertilizers if production is to be maintained (Merino *et al*. 2005). Alternative management options include selecting tree species with higher nutrient use efficiencies, lowering the planting density, increasing the rotation length, and reducing the harvesting intensity.

Even-aged versus uneven aged management

Traditionally, forest management is divided into two categories; even- and uneven-aged management. The categories are quite administrative in nature, but do represent different biological approaches to timber production and the progressions of stand structures through time. In even-aged management a stand regenerates after a disturbance which removes most of the preceding stand. This disturbance could be natural, such as a hot fire or intense windstorm, or anthropogenic, such as a clearcut. In either case trees regenerate during a short period after the disturbance and then grow as a cohort of trees quite similar in age (Oliver and Larson, 1996). In uneven-aged management the stand is not replaced after a large disturbance, but rather regenerates periodically after partial disturbances which only remove part of the stand. Trees regenerate after each disturbance, creating a stand with trees of multiple ages.

Uneven-aged management can be carried out either with a small amount of volume removed in very short cycles, such as every five years, or by larger harvests on a longer cycle, such as 20 to 25 years. The idea with light but very frequent harvests is that regeneration will occur continuously and no distinct cohorts will exist. If the harvests are heavier, but less frequent, trees will invade until the growing space is reoccupied and then there will be no new regeneration until the next cut. The stand will consist of multiple, distinct, cohorts. The silviculture system using the periodic light cuts is called single tree selection because the openings are very small. The system using periodic larger cuts and therefore bigger openings is referred to as group selection. The former results in an all-age stand and the latter in a multi-cohort stand. Both are variations of uneven-aged management.

Theoretically there should be no difference in biomass production between the various systems. Leaf area per hectare is a function of the species and the amount of available water and reaches equilibrium relatively quickly after each harvest, as soon as the growing space is reoccupied (a point often referred to as canopy closure). Differences in productivity on a given site, therefore, are a result of how much time the site is not fully occupied and the species composition. Shade-tolerant species tend to be more productive than shade-intolerant species, but often the shade-intolerant species are more commercially valuable. The lighter the harvest, the more difficult it is to establish regeneration, particularly for shade-intolerant species. This has important implications, as it means that even a very light harvest operation can significantly change the composition of a forest, moving it towards dominance by shade-intolerant species. In group selection cutting in the temperate latitudes the openings can be spaced so that light entering the stand through one opening will shine diagonally below the live crowns of the uncut trees and allow regeneration to become established throughout the stand. When light is entering through multiple openings there can be enough light for more shade-intolerant species to establish.

The greatest impact of different types of management on productivity is the frequency of stand entries with heavy ground-based harvesting equipment such as skidders. Frequent entries will compact the soil throughout the stand and reduce productivity over time unless permanent extraction trails are established and used for each entry. Even with frequent entries for thinning, it is easier to utilize a permanent trail system in even-aged stands, somewhat more difficult in group selection, and very difficult in single tree selection. Where single tree selection has been practised for some time, a dense network of permanent trails may develop: this could be seen as an adverse consequence of single tree selection systems. Logistically, the harvest system will largely dictate the economic feasibility of other silvicultural activities, and this will affect productivity. For example the costs of the management of competing non-tree vegetation are more a function of the area to be covered than the amount of vegetation; therefore it is usually only practised in even-aged management since the treatments would occur infrequently (usually only once a rotation).

Figure 4.14 Lightweight tractor being used to extract logs at Saihanba Tree Farm, Hebei Province, China. Use of smaller equipment reduces the risk of problems associated with soil compaction.

As well as the major effect of species composition on productivity, within-species genotypic variation should also be considered. Although planting can be used in uneven-aged management, there is usually reliance on natural regeneration. Natural regeneration maintains the genotypes on the site, but genetically improved stock can be used in planting, as can genotypes more suitable for the site (given that climate change may have changed the growing conditions of the site since the establishment of the previous stand). As a result, even-aged plantations using improved stock can have much higher productivity of a target tree species than an uneven-aged stand.

Short-rotation versus long-rotation

Controlling rotation length is one of the common strategies in forest management. Rotation length is defined as the period between the establishment of a stand of trees and the time when that stand is ready for the final cut. Rotation length depends on the growth performance of the tree species, its provenance, phenotypic variations, market needs, financial concerns of the landowner and other factors (e.g. mitigation of climate change effects). For example, in Finland, a short rotation length for Norway spruce (*Picea abies*) is about 30–50 years and a long rotation length is about 60–80 years (Pyörälä *et al*. 2012), while for Chinese fir (*Cunninghamia lanceolata*) in China, a short rotation length is about 10 years and a long rotation length is about 50 years (Xin *et al*. 2011).

Rotations can be calculated in a number of ways. For example, a technical rotation is the period required to produce a specified type of forest product. An economic rotation is the period over which mean annual return on investment is maximized. An ecological rotation, on the other hand, would be the time required for a site to return to the pre-harvesting ecological condition (Kimmins 2004). Intensive silvicultural practices, such as site preparation and vegetation control, reduce initial competition from woody species and thus permit the persistence of early successional species, increasing overall diversity (Jeffries *et al*. 2010). Therefore, whenever a forest is harvested, the site is reverted to an earlier stage of the ecological succession. This can be both ecologically sound and economically desirable in order to favour a particular species in the ecosystem (e.g. Douglas-fir (*Pseudotsuga menziesii*) in a predominantly western hemlock (*Tsuga heterophylla*) area, willow (*Salix*) or poplar (*Populus*) in a predominantly oak (*Quercus*) area, or Scots pine (*Pinus sylvestris*) in a predominantly Norway spruce (*Picea abies*) or silver fir (*Abies alba*) area).

However, if the disturbance is excessive it can create problems for future forest productivity. For example, the more frequent the disturbance is (or in other words, the shorter the rotation), the more prolonged are the early stages in the succession, which are usually dominated by less desirable or less productive vegetation. An alternative could be a moderate degree of disturbance (intermediate rotation length), which can be a desirable compromise between economical, technical and ecological rotations. However, if repeated at intervals shorter than the time required for complete successional recovery, such a practice can result in a gradual retrogression, ultimately reaching the same non-productive condition produced by the high degree of disturbance. A good example of this situation is the management of Chinese fir plantations in China (see below).

In terms of the renewability of resources, site nutrient capital is tightly linked to the influence of forest management on nutrient flows. As discussed earlier in this chapter, each forest has a certain capital of these nutrients which exists as a dynamic equilibrium between inputs from the atmosphere and soil weathering, and losses in stream water and other pathways. Harvesting inevitably results in some depletion of the site nutrient capital through losses in harvested materials (Blanco *et al*. 2005), as a result of disruption of the nutrient flows and retention mechanism, or as the result of other post-logging site treatments such as slash burning. These losses are replaced in time by natural inputs. However, for a given loss of nutrients on a given site, there will be a given nutrient recovery period, and if this period is shorter than that needed to replenish the nutrient pools, a reduction in site fertility will develop over time. This period can be referred to as the nutrient recovery rotation. In a sustainable forest management scheme, rotation length should be at least as long as the period to recover nutrient capitals. Otherwise, artificial nutrient inputs such as fertilization may be needed to accelerate recovery and allow for shorter rotations without endangering site productivity. However, fertilization carries risks such as eutrophication. The minimum sustainable rotation length can vary markedly among different ecosystem types, depending on the size of the nutrient pools and their flows through the trophic chains.

Rotation length also depends on the management objective. For example, for a given site, the annual mean timber production could be increased by using longer rotation lengths (60–80 years in the case of Norway spruce). However, if the same stand is managed to produce biomass for energy, this objective could be maximized by using shorter rotations of 30–50 years (Pyörälä *et al*. 2012). In this sense, the use of short rotations is becoming an increasingly promising tool in willow and poplar plantations for biomass. However, conflicting long-term effects have been reported: soil bulk density decreased, soil porosity increased and

organic matter accumulated at a study site in northeast Germany (Kahle *et al*. 2007), whereas in the United Kingdom long-term negative impacts on mammals, tree productivity and diversity have been reported (McKay, 2011). Such differences point again to the need to assess the sustainability of long or short rotations in the context of specific forest ecosystems.

International examples of intense production systems:

The proportion of the world's industrial wood sourced from intensively managed forest plantations is estimated at just over a third today and is increasing. This increase is gaving major implications for planted forests around the globe will have major consequences on the sustainability of intensive forest management. Some examples are provided below.

Loblolly pine plantations in southern U.S.A.

In North America, industrial forest harvesting is highly mechanized. Most operations are similar to those found in boreal forests and are driven by concerns about profitability, cost efficiency, and operational control. Clearcutting is frequently used to harvest mature softwood stands. In sensitive areas, various types of selective harvesting systems are practiced, both in coniferous and deciduous forests (except, until recently, in harvesting operations along the Pacific Coast). Harvesting is usually carried out by companies, contractors or small-scale loggers, regardless of the type of forest or forest ownership.

In the southern US, loblolly pine (*Pinus taeda*) is one of the most important commercial species, occupying more than 13 million ha. Within its native range loblolly pine encompasses 15 southern and Mid-Atlantic States from Delaware to Florida and west to southeastern Oklahoma. Nearly 90% of the forestland in US southern states today is in private ownership (Wicker, 2002). Loblolly pine is managed in plantations at a range of intensities (extensive to very intensive) and is used for the production of both roundwood pulp and saw logs. Although most of the pine harvest comes from non-industrial private forestland owners (NIPFs), intensively managed plantations are only found on industrial land, usually held in the form of land management corporations. Plantations owned by the NIPFs are managed at a much lower intensity.

Intensive management practices include deployment of genetically improved seedlings, cloned from fast-growing varieties. Each plantation usually includes 3-5 clonal varieties to maintain genetic diversity at the local level. Because the land is very flat, site preparation can be intensive (using both prescribed burning and chemicals) and planting can be mechanized, using bare root nursery stock, usually at densities ranging from 1,200 to 1,500 stems per hectare. Competing vegetation is aggressively controlled using an application of herbicide along each row at the time of planting and then broadly either by air (usually a helicopter) or by machine (usually a skidder) at least twice in the first 5 years. Rotations on the most intensive plantations may be 15 years

Later stand management operations generally include occasional or frequent thinnings. Fertilization is also often applied, especially in industrial plantations.

Short-rotation willow plantations for bioenergy in Europe

In Europe, timber harvesting is prohibited throughout substantial forest areas because of their special importance for biodiversity, recreation, soil and water protecton. Only 75 % of the total forest area (around 139 million hectares) is considered to be available for wood supply in the 39 countries of the European Economic Area (EEA) region. However, maintaining the economic viability of forest production remains a challenge for many European forest owners and to cope with this, forestry is expected to develop new and more intensive methods.

Increasing demands on forests as a resource for bioenergy and other products is already affecting the plantation area in Europe. The area of planted forests in the EEA region has increased over the last 15 years from 10.9 to 13.3 million hectares (almost 8% of the total forest area). This legitimate need does not necessarily conflict with biodiversity and ecosystem conditions. However, recent EU policy developments have reinforced the need for renewable energy and may lead to several countries further promoting biomass from forestry. Measures to increase forest production and/or more intensive use of forests could potentially conflict with biodiversity protection.

In areas prone to desertification, such as the Mediterranean basin, forest plantations have been promoted to combat land degradation. In northern Europe, many new plantations have been established on former abandoned or low-productivity agricultural lands. In Sweden, there have been efforts over the past 20 years to develop intensively managed willow (*Salix*) plantations to produce biomass for energy generation, while maintaining sustainable yields. Willows grow in areas with high evapotranspiration rates and high nitrogen retention rates. In addition, the ability of willow to take up heavy metals makes it suitable for multipurpose forestry, in which biomass production can be combined with water purification or as a receptor of municipal sludge (Perttu, 1999).

Willow is a pioneer species, with high light demands, and therefore competition with the understory for light can be critical. Successful establishment is usually achieved without competition with other vegetation. After establishment, willows can attain a leaf area of 6 m^2 m^{-2} or more, effectively suppressing understory growth through shading (Lindroth *et al*. 1994). Soil pH should be in the 5 to 7 range, and although it is very efficient at using water, the high levels of biomass that it can achieve makes water availability a critical issue. As a consequence, light, shallow soils with low water retention capacity should be avoided. Understory, especially perennial grasses, can be controlled by growing cereal in the field in the season before planting the willows, or by applying herbicides. Understory competition must be controlled during the establishment year. Mechanical weeding may be needed as many as three times during the first year, after bud burst and early shoot formation, taking advantage of the flexibility of willow shoots, which makes them less prone to mechanical damage.

Typical plantation densities are 10,000–15,000 trees ha^{-1}. Rotation lengths are usually in the range of 3 to 5 years in a coppice system undergoing multiple cutting cycles, although the development of faster growing clones is enabling reduced cutting cycles of 2–4 years. In southern Europe, cutting cycles can be shortened to as little as one year, but this is only possible when water and nutrients are provided in sufficient quantities to ensure the replenishment of growth reserves every year, and a 3–4 year cycle is more usual. Frost can reduce biomass production by 50%, and therefore sites exposed to late spring frosts should be avoided. For planting, 1-year old monoclonal cuttings are used, with clonal mixtures being favoured to

avoid pathogen adaptations and the spread of diseases. Planting is usually carried out mechanically, with 20 cm cuttings being taken from 2 m long willow rods; these are then pressed into the soil until only 2 cm tops protrude above soil surface (Verwijst *et al*. 2013).

To fully exploit the growth potential of willows, soil fertility must be comparable to that of agricultural fields. To maintain growth in the long term and avoid yield decline, dry sites are avoided and nutrients are added at a rate that balances the removal of nutrients though harvesting. Adequate fertilization is needed to maintain this form of intense forest management. Plantations using modern willow clones should be fertilized with at least 220 kg N ha^{-1} during the second and consecutive cutting cycles. This can be achieved with mineral fertilizers, farm animal residues or municipal organic sludge.

Figure 4.15 Willow (*Salix* sp.) being grown as short-rotation coppice for use as biomass, Uppsala, Sweden.

Harvesting is undertaken mechanically, taking into account the capacity of the soil to support heavy machinery. In northern Europe, harvesting occurs in winter, when the frozen soil can support the machinery used for harvesting, chipping and hauling the willow chips directly to where they can be consumed for heating production. This avoids the need for storing the chips. Winter harvesting also avoids the presence of leaf biomass in the harvested material, reducing nutrient exports, and resulting in a lower water content in the biomass. Expected productivities in Great Britain and northern Europe, if fertilization and understory control are done properly and fast-growing clones used, can reach between 5 an 12 Mg ha^{-1} of oven-dry

biomass (Verwijst *et al*. 2013). In southern Europe, productivity ranges 10 to 15 Mg ha^{-1} of oven-dry biomass (Vega *et al*. 2010).

As a final consideration, water use by short-rotation bioenergy plantations needs to be studied to determine the long-term sustainability of this forestry system. The relationship between water and energy is crticial for planning energy and water policies in the future. The interrelation between water, energy and CO_2 emissions exposes the complex trade-offs that arise from the use of tree energy crops. While bioenergy plantations represent an effective and viable energy source compared to fossil energies, especially in relation to the mitigation of climate change (see Chapter 8), the associated water consumption is much higher than non-renewable sources of energy. For example, poplar and willow plantations in southern Europe should be restricted to areas of high water availability (Sevigne *et al*. 2011). In such situations, woody energy crops should be applied as complement to other types of biomass such as forest and agricultural residues.

Chinese fir plantations for furniture and structural timber

China, Indonesia and Malaysia comprise over half of the forest land of Asia. All three have struggled with deforestation, and their governments are actively encouraging the development of plantation forests, which are usually oriented towards wood production, not conservation. Many such plantations are intensively managed to gain productivity. A rapidly increasing human population, demand for forest products, the increasing designation of protected forest areas and the depletion of natural forest resources are all behind this increase in plantation investment. Competition for forest land in Asia is intensifying as a range of industries such as agriculture, palm oil, and mining seek to expand their activities in forested areas. Demand for forest products is also on the rise with increasing urbanization and rising income levels (Cheng and Le Clue, 2010).

China accounts for about one-third of the plantations established globally and has seen a significant increase since 2000. A major plantation species in southeast China is Chinese-fir (*Cunninghamia lanceolata*), a subtropical coniferous tree species. It is a fast-growing species that on good sites can produce 450 m^3/ha at a final harvest age of 25–30 years. The timber of Chinese-fir is straight and decay-resistant, and has a long history as an important construction and furniture material. There has been a steady increase in its use in plantations in the past few decades, making it one of the most important timber tree species in China, accounting for 60% - 80% of the total area of timber plantations in southeast China, and for 20% - 25% of the national commercial timber output (Sheng, 1992).

Chinese-fir occurs naturally as a component of mixed subtropical evergreen broad-leaved forests. It is a species of moderate shade tolerance, but grows best in full sunlight. The species is moderately nutrient demanding, and in unmanaged natural forest it normally grows on moist and fertile sites. The response of Chinese-fir to forest fertilization varies with stand age. Growing on yellow-red earth soils, the greatest response of young Chinese-fir is to P and then to K, with little response to added N. In contrast, the greatest growth response in mid and late rotation is to N (Li *et al*. 1993).

Traditionally, Chinese-fir plantations were established after native evergreen broad-leaved forests were harvested and the slash burned. Sloping sites were sometimes terraced and intercropped with food plants

before canopy closure (see Figure 4.16 below). Plantation sites were generally abandoned after one or two rotations and allowed to regenerate naturally by stump sprouting and natural seeding to mixed species stands that acted as a fallow period to restore the site. However, since the 1950s, the plantation area of Chinese-fir has been enlarged, and this species has been repeatedly planted on the same sites without intercropping or fallow periods. Farmers have generally used a 25-year rotation, varying from 20 to 30 years depending on site quality. However, some plantations in Fujian Province are being harvested as young as 17 years or even less, a trend driven by the increasing demand for timber. With recent restrictions on the harvesting of natural forests in China, this pressure is increasing. At present, most Chinese-fir plantations are in the second or third rotation on the same sites; some are thought to be in even later rotations, but this is difficult to confirm due to a lack of documentation.

Farmers have reported yield declines in multi-rotation Chinese-fir plantations since the 1960s, but few scientifically rigorous investigations were undertaken until the late 1970s and the 1980s. A variety of competing hypotheses on the causes have been proposed, including soil nutrient depletion caused by nutrient removals in harvested materials, and/or nutrient losses by slash; physical degradation of the soil; toxic substance accumulation, including allelopathic effects; slow decomposition of Chinese-fir litter and consequent slow nutrient cycling and consequent reduced biological activities of the soil (Bi *et al*. 2007). Nutrient depletion caused by harvest removal has traditionally been considered to be one of the main factors responsible for plantation yield decline. Successive short rotations of Chinese-fir on a site will deplete the soil nutrient pool and soil carbon stocks. Over the same time period, short-rotation harvesting removes more nutrients than long-rotation harvesting because of differences in the nutrient content of sapwood and heartwood, in the proportion of sapwood and heartwood in the harvested materials, and the different quantities of nutrients removed in foliage and branches. Short rotations result in a higher frequency of site preparation by burning and the associated loss of nutrients and organic matter, and deterioration in soil physical, chemical and biological properties (Tian *et al*. 2011).

Figure 4.16 Chinese fir (*Cunninghamia lanceolata*) plantation at Xi Hao, Nanping County, Fujian, China. Note the terraces, indicating that this plantation has been established on previously cultivated land.

Based on experience, farmers assert that Chinese fir will not survive and grow well unless the site is burned prior to plantation establishment. However, there is increasing evidence that slash burning is the ultimate cause of soil degradation and site yield decline because of accelerated loss of nutrients and topsoil. One of the most serious effects of slash burning is an increase of soil erosion. In a three-year study conducted in Youxi, Fujian Province, Sheng (1992) concluded that erosion on slash-burned study sites was about 37 times greater for mineral material, 10 times greater for organic matter, and 8 times greater for the total loss of soil nutrients than that for an unburned control site. Such losses via burning are often much higher than those through harvest removals.

Figure 4.17 Chinese fir (*Cunninghamia lanceolata*) plantation at Xi Hao, Nanping County, Fujian, China. The site has been burnt following harvesting, resulting in the loss of the organic layers. Burning on a steep slope such as this can make the soil very prone to erosion.

The slash-burning of harvested Chinese-fir sites has traditionally been conducted largely to reduce competition from herbs and shrubs that can cause plantation failure if not controlled. Competition from minor vegetation has been identified as one of the main factors contributing to yield declines in second and third rotation plantations of Chinese-fir. The main problem from weeds is the vigorous sprouting of rhizomatous shrub and herb species. Sprouts of non-crop species grow much faster than their seedlings, and therefore exert much greater competition for light, moisture and nutrients. Competition from weeds is exacerbated by declines in soil fertility and tree growth, both of which reduce the competitive strength of Chinese-fir (Bi *et al*. 2007).

The TRIAD approach to the management of forested landscapes

Traditionally, the maintenance of social, economic and ecological values in a forested area has been through multi-purpose forest management. In other words, the same working forest should provide all the values. However, in the recent years a new option is gaining in popularity: dividing the forest into a number of zones for different, but complementary uses (Seymour and Hunter, 1992).

Forest production depends on the spatial scale at which is measured. With increasing spatial scale (moving from a single forest or plantation stand to the watershed or landscape level), it becomes increasingly easier to reconcile conflicting or non-complementary management objectives. In addition, in any landscape setting there will be a range of different interest priorities with regard to natural resource management represented by different stakeholders. Adopting a "landscape approach" has become incfeasingly fashionable, and is currently considered to be essential to ensure that forestry is placed in the context of othe forms of land use. If the landscape is divided into different zones, each one dedicated to different management objectives, there can be clear, specific, and effective management directions for each unit, which reduces conflicts between stakeholders by establishing a hierarchical order of uses within each zone (Côté *et al*. 2010). Zoning can also help concentrate harvesting activities in the landscape, thus minimizing anthropogenic fragmentation and the extent of the road system and optimizing economic benefits (Beese *et al*. 2003).

One of the most cited zoning strategies proposed in North America is the TRIAD (or three zone) approach proposed by Seymour and Hunter (1992), in which three different zones are established with three different sets of objectives and priorities. To maintain the ecological integrity of the forest, one zone is usually dedicated to conservation, as a network of reserves. To counterbalance the decline in wood available for harvest in the conservation zone, a wood production zone has been proposed (MacLean *et al*. 2008). The third zone is devoted to ecosystem management designed to emulate natural disturbance such as fire or windthrow. In this zone various harvesting techniques may also be applied to emulate old-growth attributes of structural and functional diversity, maintaining trees of different ages (including those over 100 or 200 years old), different types of deadwood, and more late-successional species (Gerzon *et al*. 2011).

The TRIAD concept has largely been ignored by the logging industry. It immediately represents potential losses by designating a conservation zone, and there may also be losses in the potential to harvest in the ecosystem management zone. The proposed gains in the intensive production zone are not being met as logging companies are unwilling to make the necessary investments.

Conclusions

About one third of the Earth's land surface is covered by forest, the vast majority of which has developed naturally. Once established, forest cover tends to be self-perpetuating, although the composition and structure of the forest will change over time. Nutrients within these forests are cycled, sometimes tightly. For example the majority of nutrients in a tropical rainforest are in the trees and roots – very little is stored within the soil. Consequently, when the forest is converted to agricultural crops, the nutrients are quickly exhausted.

Many problems in managed forests can be related to disturbances to the nutrient cycle; others are related to the poor choice of species for a particular site. A key skill for a forester is decide on a regeneration system that conserves the nutrients, and which also promotes the species that best meet the management objectives for the site. In some cases, those management objectives may be inconsistent with the site capability, and an adjustment will be necessary if forestry is to be successful. An added complication for all

site-based work is that site conditions are changing. For years, it was assumed that site conditions were relatively static but it is now evident that the climate is changing, and in some cases, the soil is changing due to the atmospheric deposition of nitrogen. This presents significant challenges to foresters, as it is no longer appropriate to rely on reproducing the forest present on a site prior to harvesting. The increasing prevalence of invasive weed species adds a further level of complexity.

Foresters need to be aware of these challenegs, but in some parts of the world, the official responsibility of a forester ends when regeneration has reached a "free to grow" stage (defined as a young crop of trees that is no longer impeded by competition from other species). As a result, there is no requirement to practise what in other places would be described as silviculture, namely the stewardship of a growing forest. These differences are most apparent between areas where a forest manager has a vested interest in the future forest (e.g., through private or corporate ownership) and those areas where reforestation is simply an onerous requirement associated with the (temporary) right to harvest trees in an area, usually in the form of a logging concession.

Further Reading

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